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CTSM Center for Technology and Systems Management
Technology for Intelligent Decisions

# Climate-Resilient Infrastructure:
## Adaptive Design and Risk Management

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Center for Technology and Systems Management
Department of Civil and Environmental Engineering
University of Maryland, College Park

### Our Changing Precipitation Webinar Series

A conversation on the science of precipitation and planning for the future
Session 2: From Science to Application – Climate Science, Hydrology, and Planning - Part 1
September 21, 2021

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NOAA — THE Water Research FOUNDATION

**New York City Subway Stations**

Ida 2021 | Sandy 2012

## Outline

- Background: hazards & disruptions
- Hazards: projections and extremes
- Resilience quantification (& recovery)
- Climate-resilient infrastructure
- Network resilience
- Resilience enhancing strategies
- Economics and socioeconomics
- Concluding remarks

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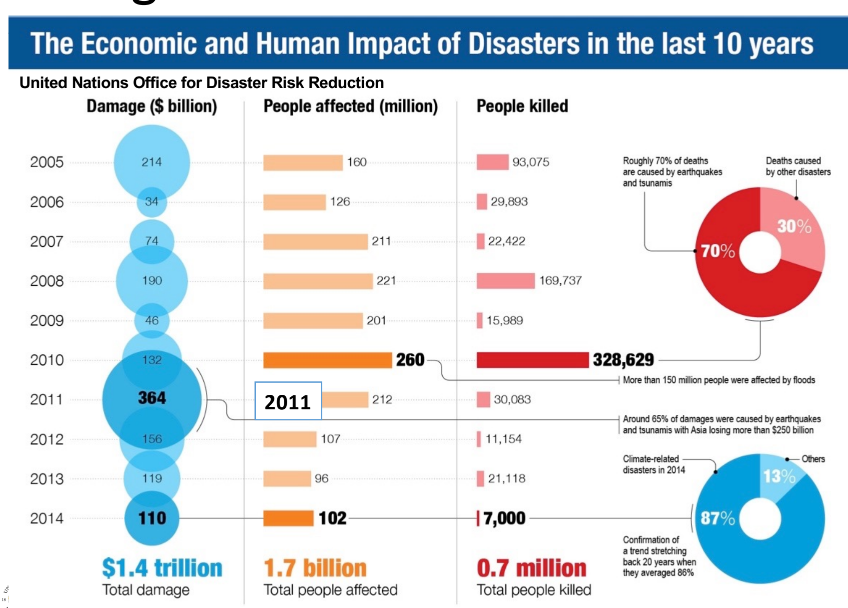
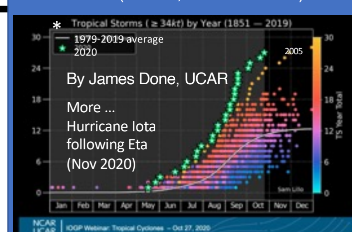
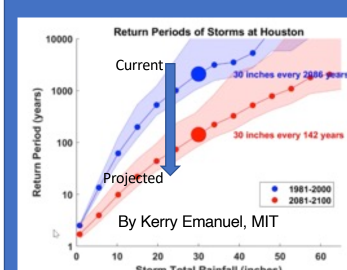
# Background: A Global Look




International Association of Oil and Gas Producers (Oct 27, 2020 Webinar)



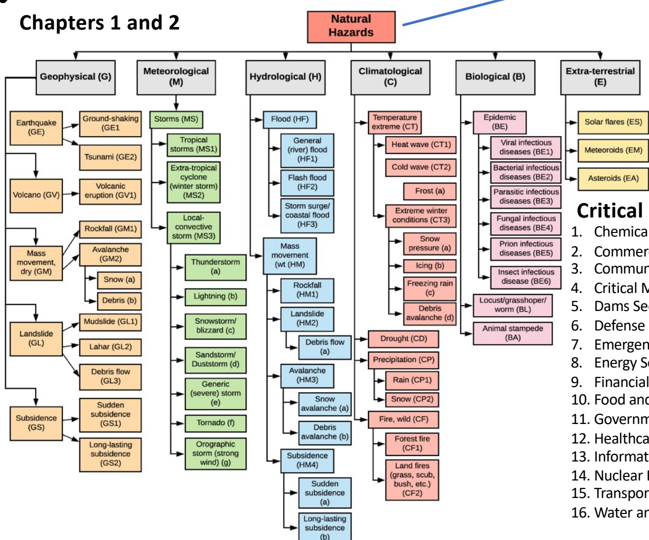



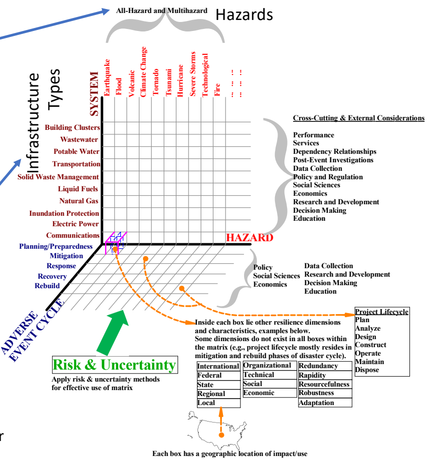

*Atlantic tropical storms (≥34knots) by year (1851-2019)

# Hazard-Resilient Infrastructure:

Manual of Practice on Analysis and Design

**Chapters 1 and 2**




**Critical Infrastructure**

1. Chemical Sector
2. Commercial Facilities Sector
3. Communications Sector
4. Critical Manufacturing Sector
5. Dams Sector
6. Defense Industrial Base Sector
7. Emergency Services Sector
8. Energy Sector
9. Financial Services Sector
10. Food and Agriculture Sector
11. Government Facilities Sector
12. Healthcare and Public Health Sector
13. Information Technology Sector
14. Nuclear Reactors, Materials, and Waste Sector
15. Transportation Systems Sector
16. Water and Wastewater Systems Sector

17 (?) Natural and Nature-based Infrastructure

Infrastructure Resilience Domain (Davis et al 2018)

**Technologies needed for integration**

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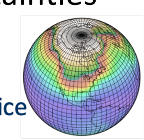
# Extreme hazard projections in a changing climate

**Primary Challenges: Global to Local Projections**

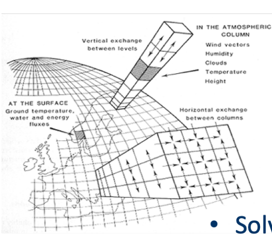
Downscaling and associated uncertainties

## Global Climate Models (GCMs)



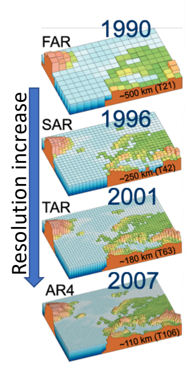
- Model atmosphere, oceans, land surface, sea ice
- Represent the ocean as 0.2° to 2° grid cells
- Represent the atmosphere as 0.5° to 4° grid cells

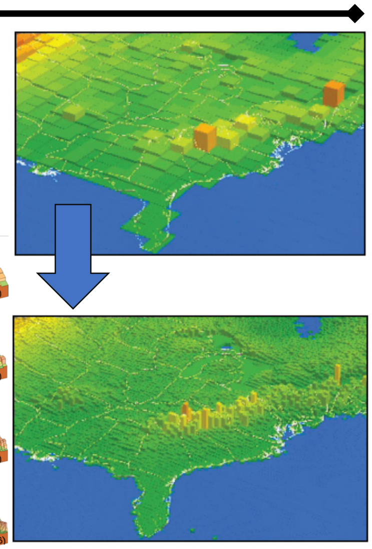
  - Use fundamental physical equations:




- Conservation of momentum
  $\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot(k_m\nabla\vec{V}) - \vec{F}_d$
- Conservation of energy
  $\rho c_v \frac{\partial T}{\partial t} = -\rho c_p(\vec{V}\cdot\nabla)T - \nabla\cdot\vec{R} + \nabla\cdot(k_T\nabla T) + C + S$
- Conservation of mass
  $\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho(\nabla\cdot\vec{V})$
- Conservation of $H_2O$ (vapor, liquid, solid)
  $\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot(k_q\nabla q) + S_q + E$
- Equation of state
  $p = \rho R_d T$

  - Solve: temperature, pressure, humidity, winds, cloud condensate, etc.



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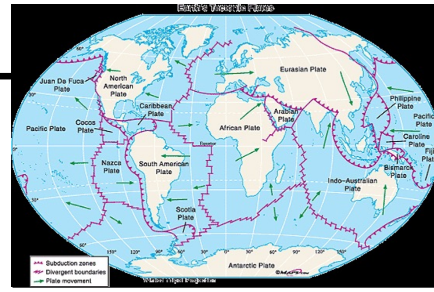
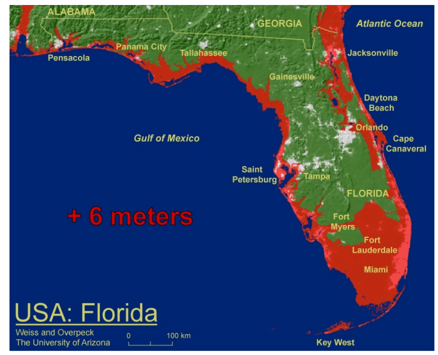
# Global and Local Sea-level Rise




- Factors affecting water level
  - Volumes of water in these basins
  - Temperature and salinity levels
  - Shapes of the sea basins
    - Tectonic plates and ocean-based volcanoes at ridges (due to water pressure changes)
  - Subsidence




**Hazard**: An increase in water volume available to feed surges and waves in coastal areas

**One foot increase → ~ Several feet increase in surge + waves**
**Depending on coastal characteristics**

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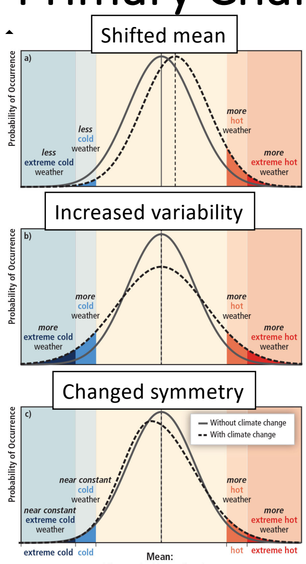
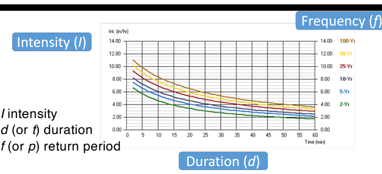
# Primary Challenges: Projections of Extremes

Precipitation as an example




Changes in internal dependencies




$I$ intensity
$d$ (or $t$) duration
$f$ (or $p$) return period

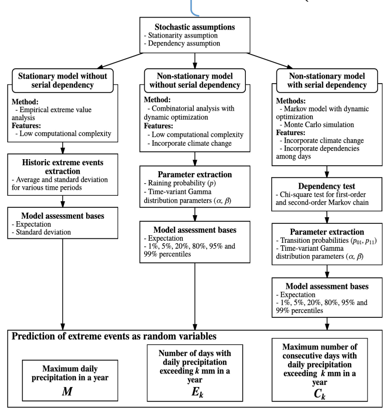
**Empirical approach:**
Model the IDF chart as a functions with tunable parameters ($a, b, c, d$): $\frac{a}{(t+b)^c}$, $\frac{a}{t^c+b}$, $\frac{af^d}{(t+b)^c}$

**Analytical approach:**
Assume daily precipitation are identically and independently distributed and apply General Extreme Value (GEV) analysis

$$F(s,\xi) = \begin{cases} e^{-(1+\xi s)^{-1/\xi}} & \xi \neq 0 \\ e^{-e^{-s}} & \xi = 0 \end{cases}$$

**Use hybrid models for intensity (I)**

**Examining the effects of non-stationarity and day-to-day serial dependency**




**M = Maximum daily precipitation per year**

**$E_k$ = No. of days of more than k mm in a year**

**$C_k$ = Maximum no. consecutive days more than k mm**

Extreme Precipitation Analysis and Prediction for a Changing Climate, H. Hu and B.M. Ayyub, ASCE-ASME J. 2018

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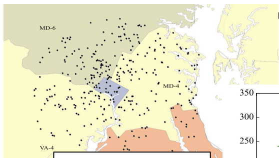
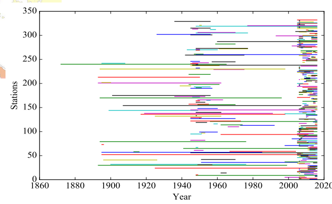
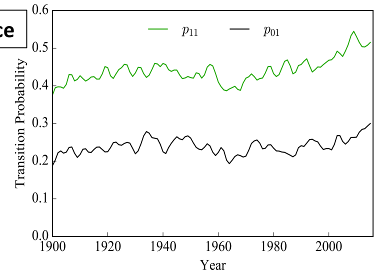
# Primary Challenges: Projections of Extremes



Data sources: Washington, DC Data

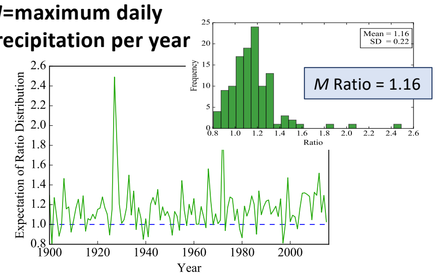



Day-to-day dependence



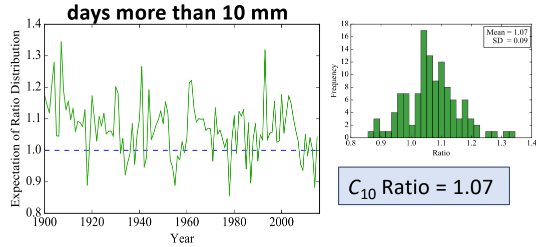

Extreme Precipitation Analysis and Prediction for a Changing Climate, H. Hu and B.M. Ayyub, ASCE-ASME J. 2018

**$M$=maximum daily precipitation per year**




$M$ Ratio = 1.16

**$C_{10}$=maximum no. consecutive days more than 10 mm**




$C_{10}$ Ratio = 1.07

**Ratio computed based on extremes with serial dependency divides by extremes without**

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# Other Adaptation Challenges

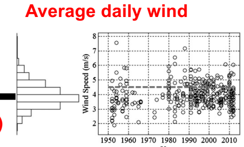
Washington DC

- Extreme precipitation and flash flooding
- Extended hot weather
- Urban heat
- Poor air quality
- Increased power consumption and failure rate
- Salty water intrusion
  - Hastened deterioration of infrastructure
- Adaptation technologies for existing infrastructure

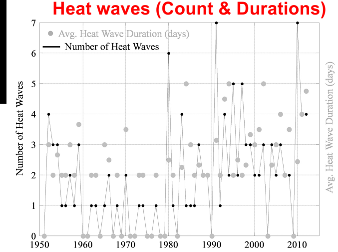
Zhang, Y., and Ayyub, B. M., 2020, "Projecting Heat Waves Temporally and Spatially for Local Adaptations in a Changing Climate: Washington…" Natural Hazards, Springer

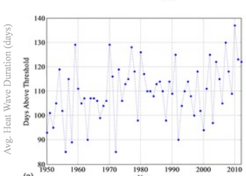
Lombardo, F. and Ayyub, B., 2015. "Analysis of Washington, DC, Wind and Temperature Extremes ..." ASCE-ASME J. Risk & Uncertainty.

**Average daily wind**

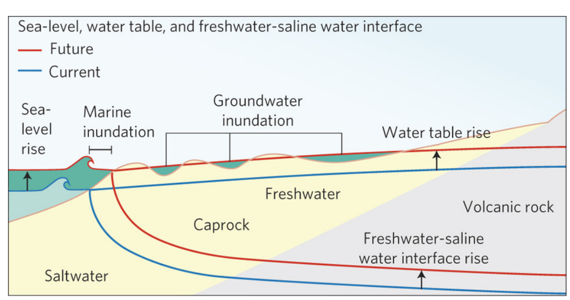



**Heat waves (Count & Durations)**




**Temperature up-crossings (days)**

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# Resilience Quantification

**Technologies needed for all stages and beyond**

Chapter 2 and 3

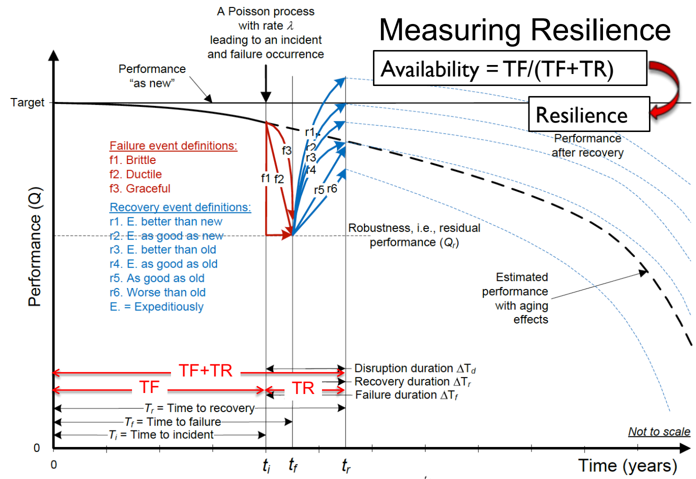
| Ductility | Redundancy | Robustness | Rapidity | Resourcefulness | Adaptability | Efficiency |
|---|---|---|---|---|---|---|

## Resilience Definitions

**Ability** to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions)

**Persistence** of its functions and performances under uncertainty in the face of disturbances

Ayyub, B. M., "Systems Resilience for Multi-Hazard Environments: Definition, Metrics and Valuation for Decision Making," Risk Analysis J., 34(2), DOI: 10.1111/risa.12093, 2014.




$$\text{Resilience}(R_e) = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$$

$R_e \geq 0$

$$\text{Failure}(F) = \frac{\int_{t_i}^{t_f} f\,dt}{\int_{t_i}^{t_f} Q\,dt} \qquad \text{Recovery}(R) = \frac{\int_{t_f}^{t_r} r\,dt}{\int_{t_f}^{t_r} Q\,dt}$$

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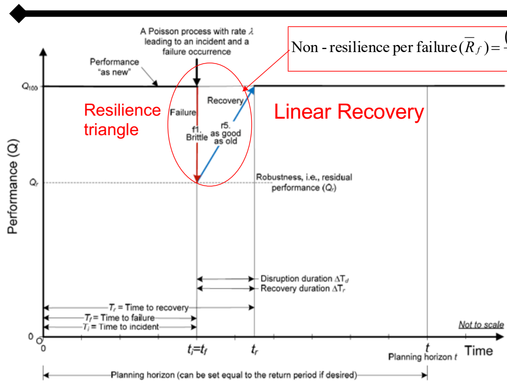
# Resilience: Practical Models

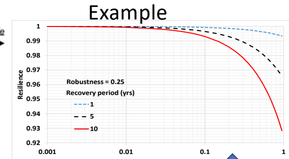
$$\text{Non-resilience per failure}(\bar{R}_f) = \frac{(t_r - t_i)(Q_{100} - Q_r)}{2Q_{100}t}$$

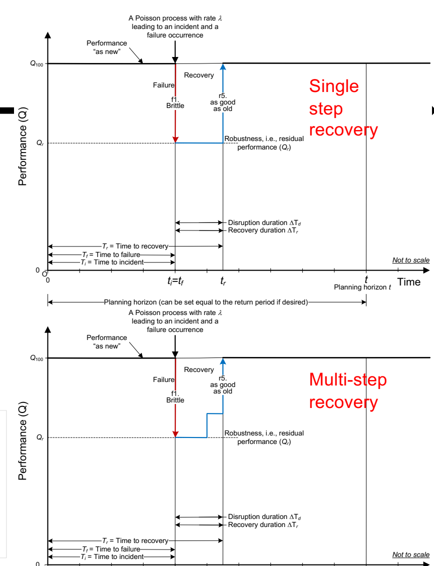



These models account for:

- Event rate
- Failure probability
- Initial and residual (robustness) capacities
- Duration of disruption
- Practical recovery profile
- Non-resilience (resilience triangle)
- Planning horizon

Example




$$\text{Resilience}(R_e) = 1 - \sum_{x=1}^{\infty}\left(\exp(-\lambda t)\frac{(\lambda t)^x}{x!}p^x \bar{R}_f^x\right)$$

$p$ = failure probability for one load or demand encounter

$$\text{Resilience}(R_e) = 1 - \exp\left(-\lambda t\left(1 - p\bar{R}_f\right)\right) + \exp(-\lambda t)$$

**Special Case:**

Planning horizon ($t$) is equal to the return period ($1/\lambda$):

$$\text{Resilience}(R_e) = 1 - \exp\left(-\left(1 - p\bar{R}_f\right)\right) + \exp(-1)$$

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# Measuring Performance

**Chapter 2 and 3**

## Examples

- Transportation: **Roads**
- <u>Network</u> topology: efficiency
- Community **wellbeing**

Aggregated
Versus
Integrated

**Multi-dimensional Performance: water distribution**

- Fire hydrants: volume and pressure
- User consumption: volume and quality
- Delivery: reliability

Credit: Dr. C. Davis

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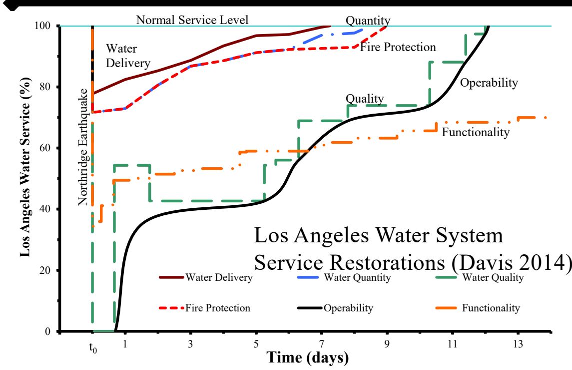
| SYSTEMS | PERFORMANCE | UNITS |
|---|---|---|
| **Houses and buildings** | Space availability<br>Elevation | Area per day<br>Distance above water level |
| **Transportation: Roads** | Throughput traffic | Count per day |
| **Facilities:<br>Water treatment plants** | Water production capacity | Volume per day |
| **Infrastructure: Water delivery** | Water available for consumption | Volume |
| **Coastal protection:<br>Vegetation and dunes** | Protection provided | Level of protection in terms of surge/wave height), width and/or volume |
| **Electric power distribution** | Power delivered | Power per day |
| **Communication: Wireless** | Capacity | Volume per day |
| **Healthcare: Clinics** | Patients per day | Count per day |
| **Communities** | Economic output<br>Quality of life (consumption) | Dollars<br>Dollars |

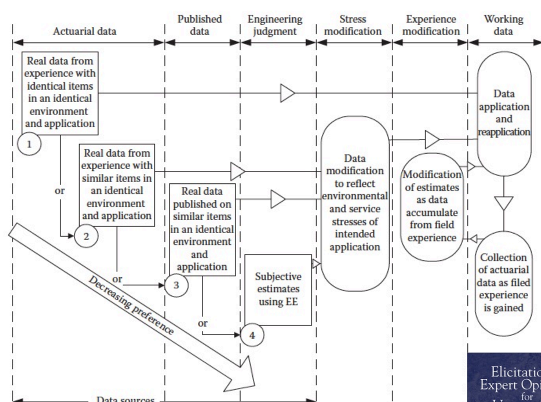


# Multi-dimensional Performance and Data Needs

**Chapter 2 and 3**

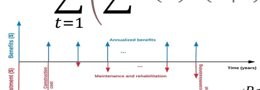



## Data needs, sources and uncertainty




## Loss accumulation models (Chapter 4)

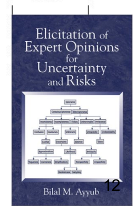
$$L = \sum_{t=1}^{T} \left( \sum P(E)P(H|E)P(F|H)(L|F)e^{-it} \right)$$



$$P\left(\frac{Benefit}{Cost} \geq 1\right) = P(Cost - Benefit \leq 0)$$

where:

| | |
|---|---|
| $L$ | Loss ($L$) accumulated over the planning horizon represented by the time period $T$ |
| $P(E)$ | Probability of an event ($E$) or related scenario at time $t$ |
| $P(H|E)$ | Annual probability of a hazard ($H$) under the conditions defined by $E$ |
| $P(F|H)$ | Probability of a failure ($F$) upon the occurrence of $H$ |
| $L|F$ | Loss ($L$) upon the occurrence of $F$ |
| $i$ | Annual discount rate |

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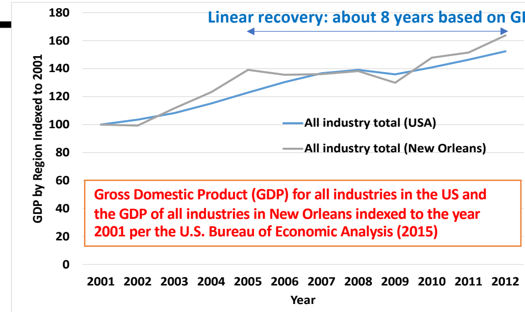
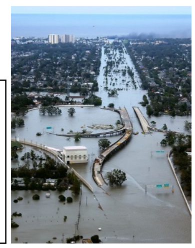
# Recovery Profile: New Orleans and Hurricane Katrina, August 23–31, 2005


**City of New Orleans Ground Elevations**
From Canal St. at the Mississippi River to the Lakefront at U.N.O.




Most destructive natural disaster in American history, 90,000 mi² (233,000 km²) of land impacted, an area the size of the United Kingdom

- Total direct damage $108 billion (in 2005 US$)
- Direct and indirect fatalities 1,833
- Insurance claims fulfilled of $41.1 billion (private) and $16.1 billion (public)
- Post-Katrina protections of $120.5 billion on the Gulf Region



- Challenges in characterizing recovery
  - Multidimensionality
  - Transfers to other regions
  - Disruptions during recovery
- Population growth has not kept up with the GDP growth
  - Perhaps attributable to changes in the composition of the industries, population skill levels, and incomes

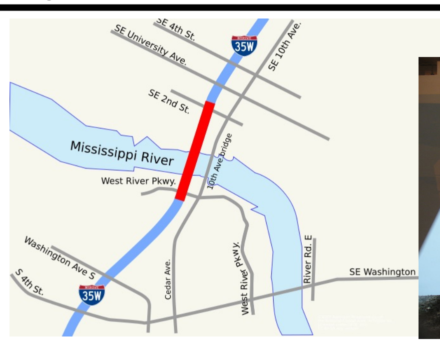


# Recovery Profile: Bridge Failure

**Technology**: Seismic structural fuses

August 1, 2007

**Fatigue failure**




**After**

Eight lane (Interstate 35 W crossing the Mississippi River in Minneapolis)
Steel truss arch bridge collapsed during rush hour
Deaths = 13, Injuries = 145, Average daily traffic = 140,000 vehicles
Replacement bridge fast-tracked opened on September 18, 2008

**Single-step recovery**

Recovery time:
About one year

Bridge robustness:
0%

Recovery profile:
A single-step recovery profile

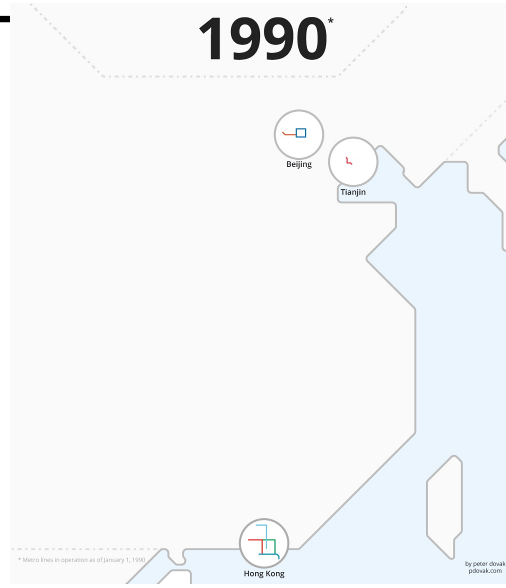
# Lifeline Infrastructure: Network Resilience

**In collaboration with Tongji University: Tunnels and Metro Systems**

Team: B. M. Ayyub, Y. Saadat, Y.J. Zhang, D.M. Zhang, F. Du, H.W. Huang, and M. Beer

Shanghai

**Railroads: Passengers and Freight**

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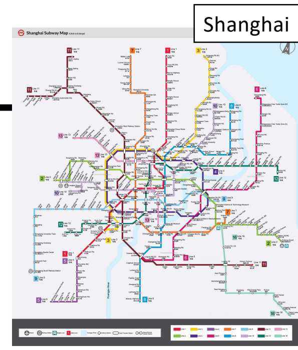
# Ongoing Work: Resilience of Networks

- Tunnels
  - Performance
  - Quantification of resilience
  - Enhancement of resilience
- Metro systems
  - Network definition
  - Interconnectedness and network vulnerability
  - Network resilience
  - Enhancement strategies
- Hazards
  - Water (surge and wave) level rise
  - Flooding of stations

Zhang, F., Du, F., Huang, H., Zhang, D., Ayyub, B. M., and Beer, M., 2018. "Resiliency Assessment of Urban Rail Transit Networks: Shanghai Metro as an Example," Safety Science, Elsevier, Volume 106, July 2018, Pages 230–243, https://doi.org/10.1016/j.ssci.2018.03.023.

Saadat, Y., Ayyub, B. M., Zhang, Y. J., Zhang, D. M., and Huang, H. W. 2019. "Resilience of Metrorail Networks: Quantification with Washington D.C. as a Case Study," ASCE-ASME J. Risk Uncertainty Eng. Syst., Part B: Civ. Eng., doi:10.1115/1.4044038

Shanghai



Washington DC

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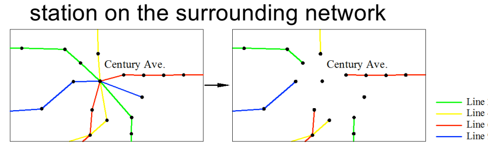
# Characteristic of Shanghai Metro Network

| Characteristic of Network | Calculated value for Shanghai metro |
|---|---|
| Node $N$ | 303 |
| Link | 350 |
| Average node degree $k^*$ | 2.31 |
| Characteristic path length $L$ | 14.87 |
| Diameter of network $D$ | 41 |
| Network cluster coefficient $C$ | 0.0082 |
| Limit state of $L$ ($\ln N / \ln k^*$) | 6.82 |
| Limit state of C ($k^* / N$) | 0.0076 |

Ranking of Node Vulnerability (Topology)

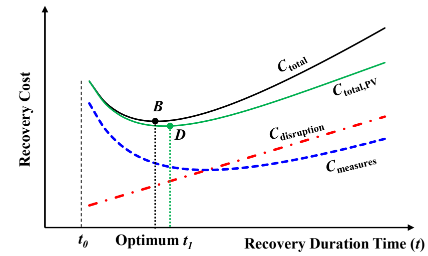
| No. | Removed node | Vulnerability $V$ |
|---|---|---|
| 1 | Caoyang Rd. Stn. | 0.0073 |
| 2 | Shanghai Railway Stn. | 0.0066 |
| 3 | Siping Rd. Stn | 0.0065 |
| 4 | Zhenping Rd. Stn. | 0.0065 |
| 5 | Longyang Rd. Stn. | 0.0062 |

The effect of failure of Century Ave station on the surrounding network

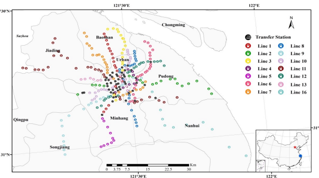



The $R_e$ of different line recovery sequence

| Recovery sequence(*) | $R_e$ | Recovery sequence | $R_e$ |
|---|---|---|---|
| 2-6-9-4 | 0.974 | 6-4-2-9 | 0.968 |
| 2-6-4-9 | 0.973 | 4-2-9-6 | 0.967 |
| 6-2-9-4 | 0.973 | 4-6-2-9 | 0.967 |
| 6-2-4-9 | 0.972 | 9-2-4-6 | 0.966 |
| 2-9-6-4 | 0.971 | 6-9-4-2 | 0.965 |
| 2-4-6-9 | 0.971 | 4-9-2-6 | 0.964 |
| 2-4-9-6 | 0.970 | 6-4-9-2 | 0.964 |




Zhang, Y. J., Ayyub, B. M., Zhang, D. M., Saadat, Y., Huang, H. W., 2018 (Submitted). "Vulnerability Assessment of a Double-Weighted Metrorail Transit Network: Shanghai Metro as an Example," J. of Infrastructure Systems, ASCE.

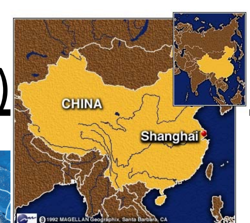


Best recovery sequence

| Metro Station | Best metro line recovery sequence |
|---|---|
| Xujiahui Stn. | 11-1-9 |
| Shanxi Rd.(S) Stn. | 12-10-1 |
| People's Square Stn. | 2-8-1 |
| Hanzhong Rd. Stn. | 1-12-13 |

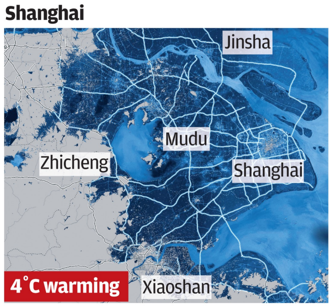


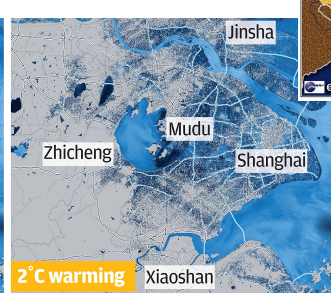
# Impacts of Sea Level Rise on Shanghai Metro Network (2016)



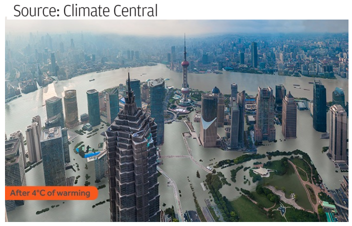


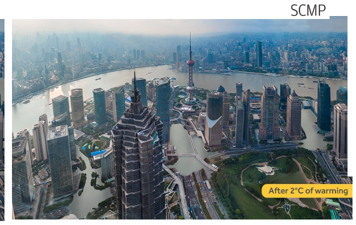
Shanghai

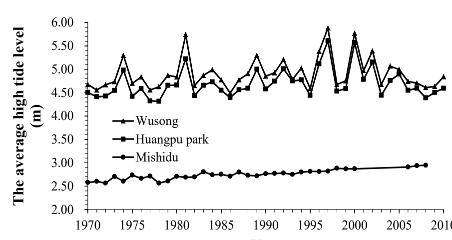



Source: Climate Central SCMP

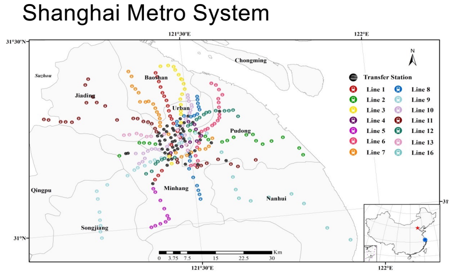


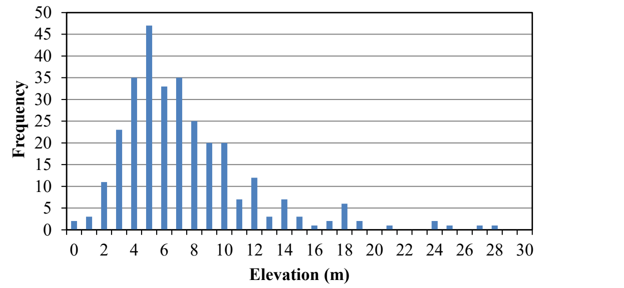



# Impacts of Water Level Rise on Shanghai Metro Network

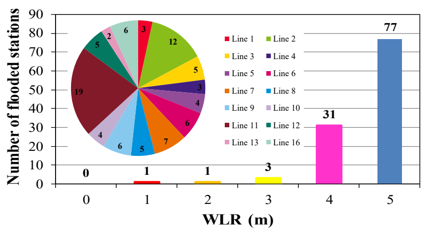
Shanghai Metro System

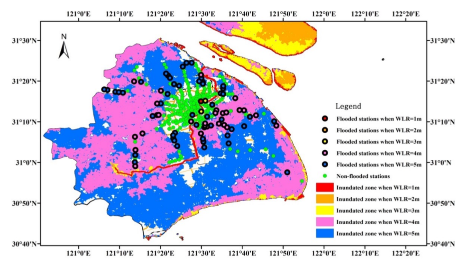



Histogram of the Ground Elevation of Shanghai Metro Stations




Inundation Maps of Shanghai, as an Example Using Hypothetical WLR of 1 m, 2 m, 3 m, 4 m, and 5 m

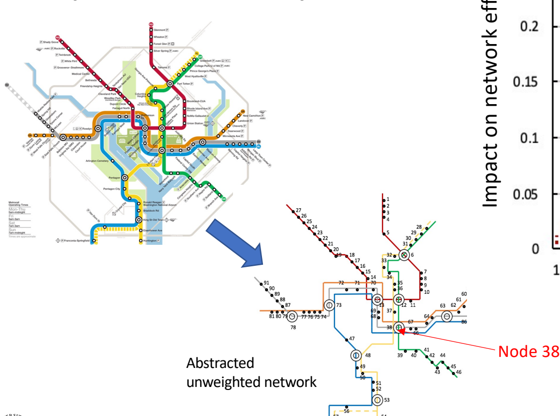


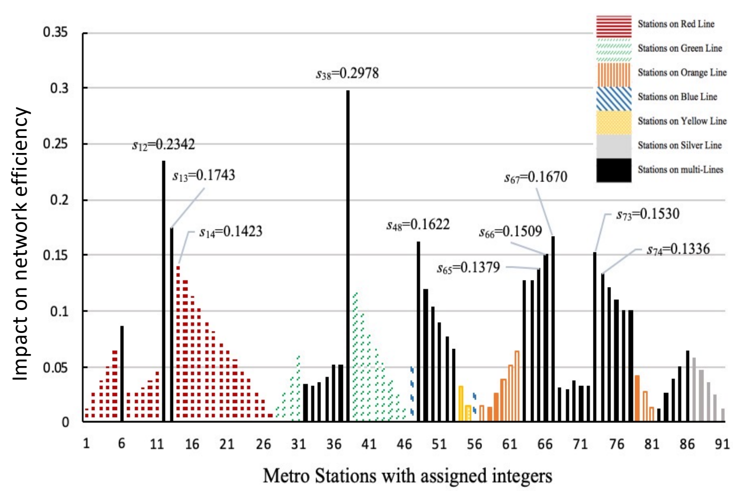






# Washington D.C. Metro

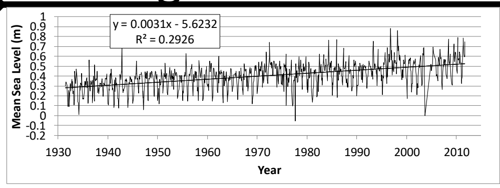
**Vulnerability of Washington D.C. Metro network subjected to node loss (Saadat et al 2019)**

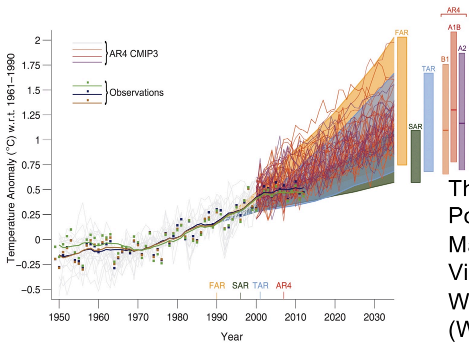



Saadat, Y., Ayyub, B. M., Zhang, Y. J., Zhang, D. M., and Huang, H. W. 2019. "Resilience of Metrorail Networks: Quantification with Washington D.C. as a Case Study," ASCE-ASME J. Risk Uncertainty Eng. Syst., Part B: Civ. Eng., doi:10.1115/1.4044038

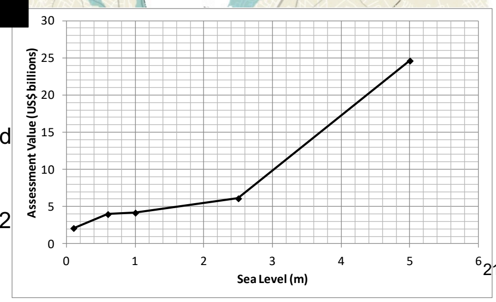
# Impacts of Sea Level Rise on Washington DC




Ayyub, B. M., Braileanu, H. G., and Qureshi, N., 2012, "Prediction and Impact of Sea Level Rise on Properties and Infrastructure of Washington, DC," Risk Analysis Journal, Society for Risk Analysis, online 2011 Oct 28, 1-18. doi: 10.1111/j.1539-6924.2011.01710.x. Picked up by ~300 media channels including CNN, Wall Street Journal, Washington Post, etc.


The Impact of a Powerful Hurricane Making Landfall around Virginia Beach, on Washington, DC (Washington Post 2012 based on Results by Ayyub et al. 2012)

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# Infrastructure for Community Resilience

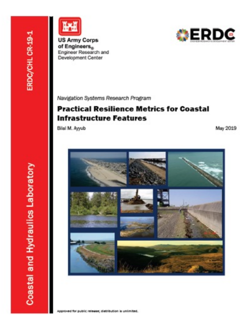
- **Need**
  Infrastructure resilience necessary for supporting community resilience
- **Objective**
  Development or enhancement of best practices and standards for resilient infrastructure
- **Manuals of Practice (MOPs) and ASME Guidance Documents**
  General documents for all hazards and all systems with needs to develop hazard-specific or sector-specific documents (e.g., electric-power distribution Guides)

**Hazard**-Resilient Infrastructure (**ASCE MOP144, 2021**)


**General** for **all hazards** and **all Systems**

**Climate**-Resilient Infrastructure (**ASCE MOP140, 2018**)


**Practical Resilience Metrics for Coastal Infrastructure Features** (**USACE, 2019**)

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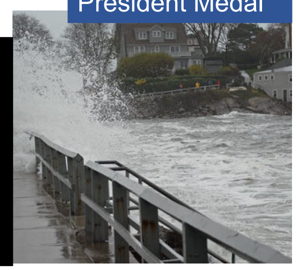
# Infrastructure: Needs

- 2018 U.S. Census Bureau statistics: about $1.3 trillion in infrastructure in the U.S. a year including bridges, buildings, power plants, and much more
- Most likely are not designed to account for a changing climate.
- With a design life of 50 or 100 years, or even longer, these projects are going to experience greater hazards and more extremes than they are designed for

2017 ENR Newsmaker


**Uncertainties**
Known unknowns → *Reliability-based or Robust design*
Unknown unknowns → *Adaptive design*

2019 ASCE President Medal



ASCE News Jan 2019

The dilemma for engineers is that the past does not represent the future

Ayyub, B. M., Medina, M., Vinson, T., Walker, D., Wright, R. N., AghaKouchak, A., Barros, A. P., Cerino, A. C., Conray, R. P., Fields, R. E., Francis, O. P., Olsen, J. R., Samaras, C., and Vahedifard, F., 2018. Climate-Resilient Infrastructure: A Manual of Practice on Adaptive Design and Risk Management. Edited by B.M. Ayyub, ASCE Manual of Practice (MOP) 140, American Society of Civil Engineers, Reston, VA. Interviewed by ASCE News: https://news.asce.org/at-the-crossroads-of-civil-engineering-and-climate-change/

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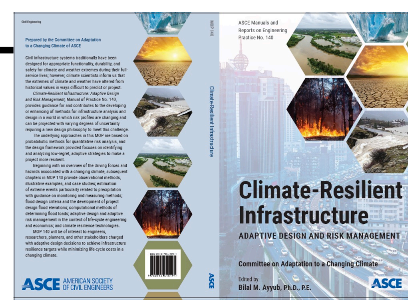
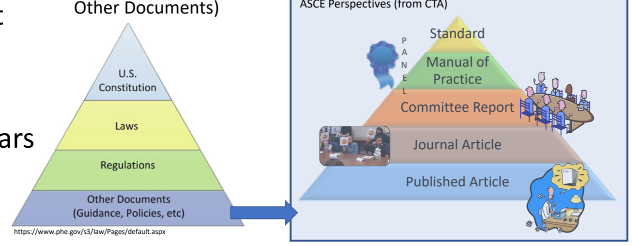
# Offered to Planners and Engineers

ASCE Manual of Practice #140 (2018)




- Framework of the Manual of Practice
  - Non-prescriptive
  - Quantitative: probabilistic
  - Analytic methods with native measurement units of potential losses that would support economic valuation and benefit/cost analysis
  - Adaptive solutions based on the concept of real options
- A step towards developing standards
  - Development of standards could take years
  - An interim solution

Legal (ASCE pyramid is under Other Documents)

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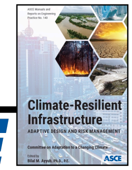
# ASCE Manual of Practice #140 (2018)




## Content

Chapter 1. Introduction

**Chapter 2. A Changing Climate: Problem Definition** Hazards

Chapter 3. Observational Method

Chapter 4. Characterization of Extremes and Monitoring

Chapter 5. Flood Design Criteria

Chapter 6. Flood Loads

**Chapter 7. Adaptive Design and Risk Management** Key chapter – see example

Chapter 8. Data and Information Sources

Appendix A. Terminology

**Appendix B. ASCE Standards and Climate Change** Needs

Appendix C. Methodology for Statistical Computations

**Appendix D. Adaptation Technologies** Needs

ASCE American Society of Civil Engineers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**Additional Reviews by Organization**
American Meteorological Society
Water Utility Climate Alliance

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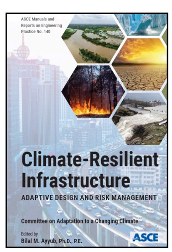
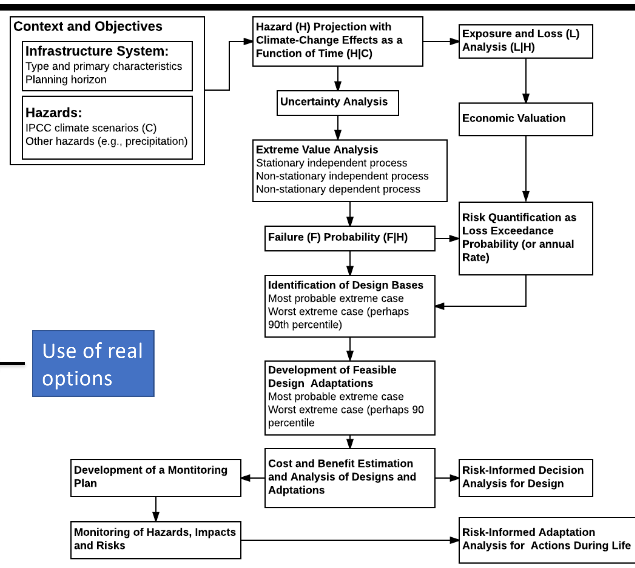
# Methodology (Framework)

Chapter 7. Adaptive Design and Risk Management

- Context and Objectives
- Hazard Identification and Projection
  - Uncertainty Analysis
  - Extreme Value Analysis
- Failure Probability Estimation
- Economics of climate resilience
  - Exposure and Loss Analysis
  - Economic Valuation
- Risk Quantification as Loss Exceedance Probabilities
- Development of Feasible Design Adaptations for Decision Making
  - Cost and Benefit Estimation and Analysis
  - Risk-Informed Decision Analysis
- Hazard and Risk Monitoring
  - Risk-Informed Adaptation Analysis for Actions During Life




Use of real options

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ASCE American Society of Civil Engineers

# Methodology (Underlying Model)

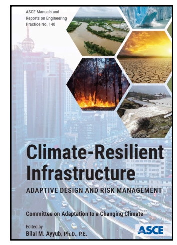
Chapter 7. Adaptive Design and Risk Management

Quantifying climate risk for a system brings together the probabilities and consequences in terms of a loss ($L$) random variable as follows:

$$L = \sum_{t=1}^{T}\left(\sum P(E)P(H|E)P(F|H)(L|F)\mathrm{e}^{-\mathrm{it}}\right)$$

where

| | |
|---|---|
| $L$ | Loss ($L$) at time $t$ |
| $P(E)$ | Probability of an event ($E$) or climate related scenario at time $t$ |
| $P(H\|\mathrm{E})$ | Annual probability of a hazard ($H$) under the conditions defined by $E$ |
| $P(F\|H)$ | Probability of a failure ($F$) upon the occurrence of $H$ |
| $L\|F$ | Loss ($L$) upon the occurrence of $F$ |
| $i$ | Annual discount rate |






# ASCE Standards and Adaptation to a Changing Climate

Appendix B. ASCE Standards and Climate Change

Source: MOP 140 Needs

Table B-1. ASCE Standards and Sensitivity to Changes in Weather and Climate Extremes.

| Complete reference number | Title of standard | Sensitivity grouping* |
|---|---|---|
| ANSI/ASCE 1-82 | N-725 Guideline for Design and Analysis of Nuclear Safety-Related Earth Structures | II |
| ANSI/ASCE 3-91 | Standard for the Structural Design of Composite Slabs | I |
| ASCE 4-98 | Seismic Analysis of Safety-Related Nuclear Structures and Commentary | III |
| ASCE/SEI 5-13 and 6-13 | Building Code Requirements and Specification for Masonry Structures | III |
| ASCE/SEI 7-10 | Minimum Design Loads for Buildings and Other Structures | I |
| SEI/ASCE 8-02 | Specification for the Design of Cold-Formed Stainless Steel Structural Members | I |
| ANSI/ASCE 9-91 | Standard Practice for Construction and Inspection of Composite Slabs | I |
| ASCE/SEI 10-15 | Design of Latticed Steel Transmission Structures | I |
| SEI/ASCE 11-99 | Guideline for Structural Condition Assessment of Existing Buildings | III, IV |
| ANSI/ASCE/EWRI 12-13 | Standard Guidelines for the Design of Urban Subsurface Drainage | III, IV |
| ANSI/ASCE/EWRI 13-13 | Standard Guidelines for the Installation of Urban Subsurface Drainage | III, IV |
| ANSI/ASCE/EWRI 14-13 | Standard Guidelines for the Operation and Maintenance of Urban Subsurface Drainage | III, IV |
| ASCE 15-98 | Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD) | IV |
| AF&PA/ASCE 16-95 | Standard for Load and Resistance Factor Design (LRFD) for Engineered Wood Construction | I |
| ASCE 17-96 | Air-Supported Structures | I |
| ASCE/SEI 19-10 | Structural Applications of Steel Cables for Buildings | I |
| ASCE 20-96 | Standard Guidelines for the Design and Installation of Pile Foundations | IV |
| ANSI/ASCE/T&DI 21-13 | Automated People Mover Standards | I, IV |
| ASCE/SEI 24-14 | Flood Resistant Design and Construction | II |

Table B-1. (Continued)

| Complete reference number | Title of standard | Sensitivity grouping* |
|---|---|---|
| ASCE 26-97 | Standard Practice for Direct Design of Buried Precast Concrete Box Sections | III |
| ASCE 27-00 | Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction | III |
| ASCE 28-00 | Standard Practice for Direct Design of Precast Concrete Box Sections for Jacking in Trenchless Construction | III |
| ASCE/SEI 31-03 | Seismic Evaluation of Existing Buildings | III |
| SEI/ASCE 32-01 | Design and Construction of Frost-Protected Shallow Foundations | IV |
| EWRI/ASCE 33-01 | Comprehensive Transboundary International Water Quality Management Agreement | II, III |
| EWRI/ASCE 34-01 | Standard Guidelines for Artificial Recharge of Ground Water | III |
| ASCE/EWRI 40-03 | Regulated Riparian Model Water Code | III |
| ASCE/SEI 41-13 | Seismic Evaluation and Retrofit of Existing Buildings | III |
| ASCE/SEI 43-05 | Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities | III |
| ASCE/EWRI 45-05 | Standard Guidelines for the Design of Urban Stormwater Systems | II, III, IV |
| ASCE/EWRI 47-05 | Standard Guidelines for the Operation and Maintenance of Urban Stormwater Systems | II, III, IV |
| ASCE/SEI 48-11 | Design of Steel Transmission Pole Structures | I |
| ASCE/SEI 52-10 | Design of Fiberglass-Reinforced Plastic (FRP) Stacks | I |
| ANSI/ASCE/EWRI 56-10 | Guidelines for the Physical Security of Water Utilities | II |
| ANSI/ASCE/EWRI 57-10 | Guidelines for the Physical Security of Wastewater/Stormwater Utilities | II |
| ASCE/EWRI 60-12 | Guideline for Development of Effective Water Sharing Agreements | II, III |

*** Grouped as follows:**

**I. Change in loading**

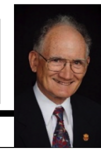
**II. Change in surface hydrology (including flood extent or frequency, or inundation owing to sea level rise)**

**III. Change in groundwater table height (including that owing to sea level rise)**

**IV. Changes in temperature**

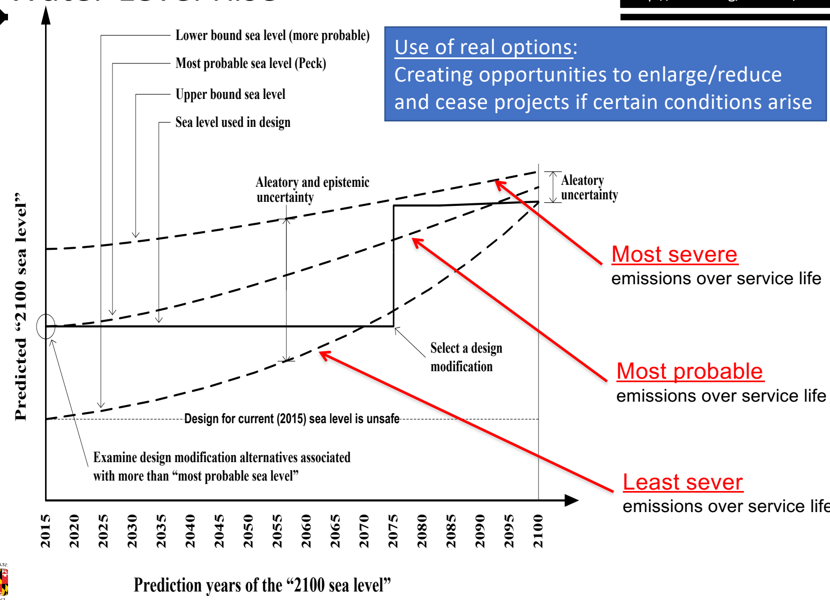
# Example: Adaptive Design for Water Level Rise

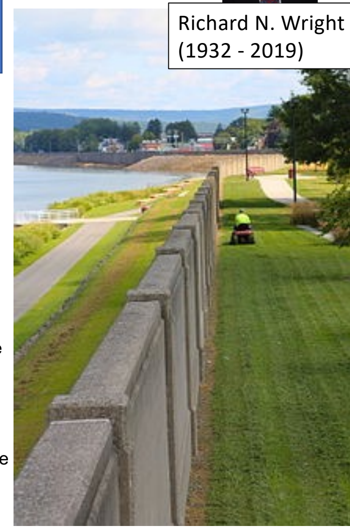
Ayyub, B. M., and Wright, R. N., 2016. "Adaptive Climate Risk Control of Sustainability and Resilience for Infrastructure Systems," Editorial, J Geography and Natural Disasters, 6(2), http://dx.doi.org/10.4172/2167-0587.1000e118.



Richard N. Wright III (1932 - 2019)

Use of real options:
Creating opportunities to enlarge/reduce and cease projects if certain conditions arise





# Example: LOSSAN Adaptive Design

Use of real options

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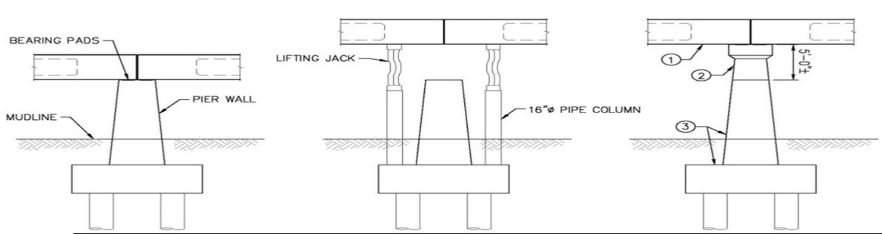
LOSSAN (Los Angeles to San Diego) Rail Corridor follows the sea coast and crosses low-lying areas on trestles

Uses precast piers and caps to allow insertion of additional pier segments if needed to adapt to flooding hazard




Dial, R., Smith, B., and Rosca, Jr., G., "Evaluating Sustainability and Resilience in Infrastructure: Envision™, SANDAG and the LOSSAN Rail Corridor," Proceedings of the 2014 International Conference on Sustainable Infrastructure, American Society of Civil Engineers, pp 164-174. ISBN 978-0-7844-4

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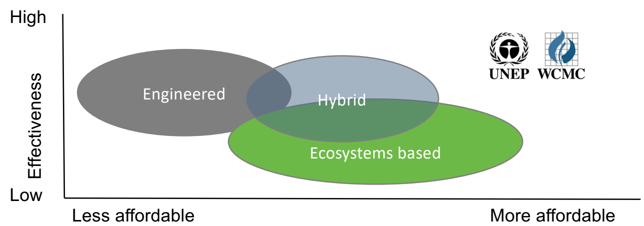
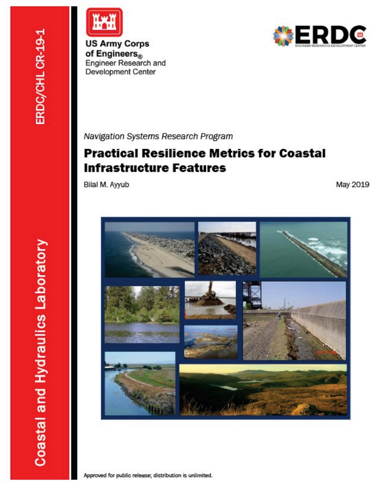
# Nature-Based and Natural Solutions

- **Nature-Based Solutions:** Use of natural or semi-natural areas or systems to mitigate environmental impacts, increase efficiency or secure ecosystem services (barrier islands, vegetations, etc.)
- **Natural Infrastructure**: Strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecosystem values and functions with benefits to humans (dunes, vegetations, etc.)
- **Ecosystem-Based Adaptation:** use of biodiversity and ecosystem services as part of an overall adaptation strategy (related concepts: soft engineering, eco-disaster risk reduction, nature-based defences, green infrastructure)




UNEP WCMC

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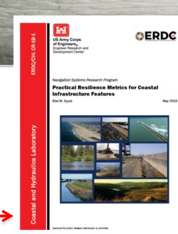
United Nations Environment World Conservation Monitoring Center



# Strategies to Enhance Resilience
**(Chapter 5)**






- Hardening systems
  - Land-use/associated policies
  - System designs
  - Technologies, such as using engineered weak-points in systems acting like fuses
- Soft solutions
  - Natural and nature-based infrastructure
  - Insurance and insurance securities
  - Social programs, governmental help for recovery
  - Societal measures, such as private programs

Ayyub, B. M., Pantelous, A., and Shao, J., 2016. "Towards Resilience to Nuclear Accidents: Financing Nuclear Liabilities via Catastrophe Risk Bonds" ASCE-ASME J. Risk Uncertainty Eng. Syst., Part B: Mechanical Eng., DOI: 10.1115/1.4033518.

**Technologies: sensors, drones, imaging, etc.**

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# Performances: Natural and Nature-Based Features

## Examples

- Dunes and beaches
  - Berm height and width
  - Beach slope
  - Sediment grain size and supply
  - Dune height, crest and width
  - Presence of vegetation
- Vegetated features, e.g., marshes
  - Marsh, wetland or submerged aquatic vegetation
  - Elevation and continuity
  - Vegetation type and density
  - Spatial coverage and health

Quantification: essential for risk management

Resilience: recovery and multiple events


| Types | Dunes and Beaches | Vegetated Features (e.g., marshes) | Oyster and Coral Reefs | Barrier Islands | Maritime Forests/Shrub Communities |
|---|---|---|---|---|---|
| Benefits | Breaking of offshore waves, Attenuation of wave energy, Reduction or prevention of inland water transfer | Breaking of offshore waves, Attenuation of wave energy, Reduction or prevention of inland water transfer, Increased infiltration | Breaking of offshore waves, Attenuation of wave energy, Slowing of inland water transfer | Wave attenuation and/or dissipation, Sediment stabilization | Wave attenuation and/or dissipation, Shoreline stabilization, Soil retention |
| Performance factors | Berm height and width, Beach slope, Sediment grain size and supply, Dune height, crest, and width, Presence of vegetation | Marsh, wetland, or submerged aquatic vegetation elevation and continuity, Vegetation type and density, Spatial extent | Reef width, elevation, and roughness | Island elevation, length, and width, Land cover, Breach susceptibility, Proximity to mainland shore | Vegetation height and density, Forest dimension, Sediment composition, Platform elevation |


USACE 2013
Ayyub 2019

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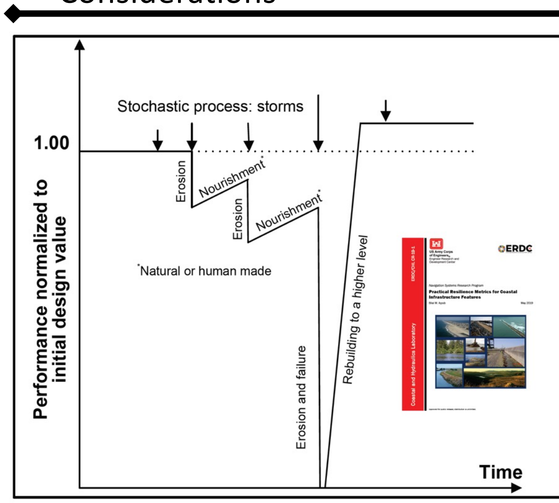
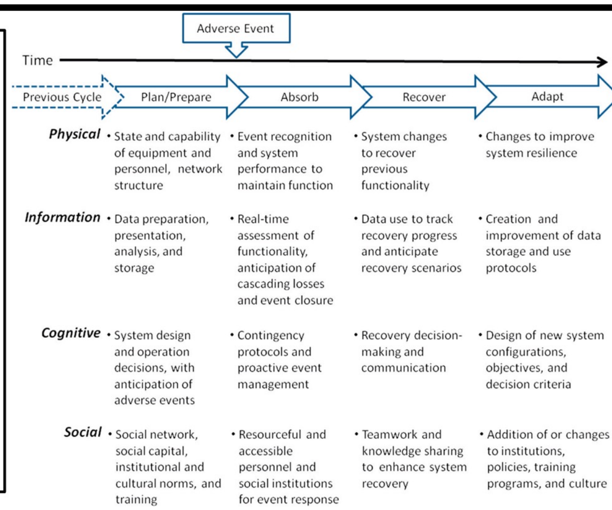
# Performances: Natural and Nature-Based Features

## Considerations




Linkov et al. 2013

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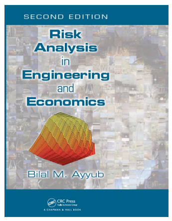
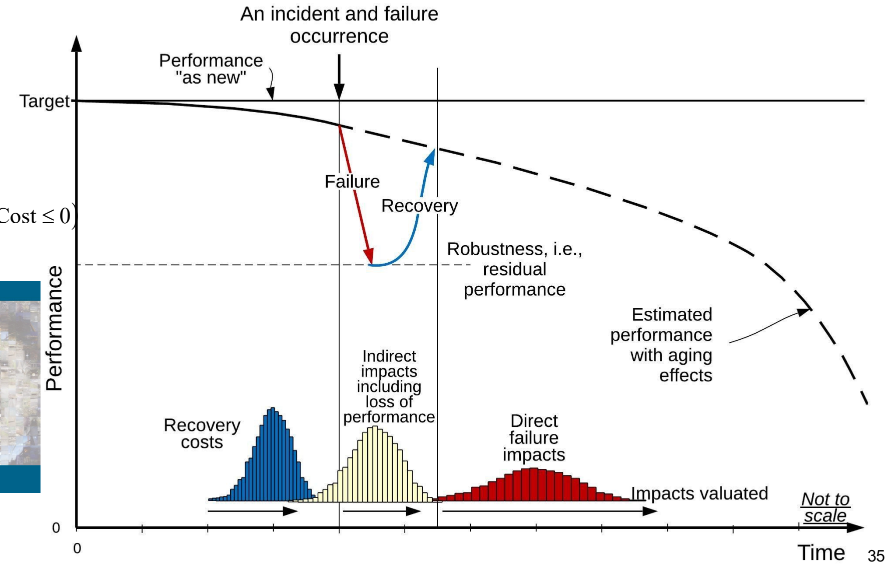
# Economic Valuation of Resilience

Gilbert, S., and Ayyub, B., 2016. "Models for the Economics of Resilience," ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civil Eng., DOI: 10.1061/AJRUA6.0000867.

**Willingness to pay**
**Decision analysis**
**Discount rates**
**Tradeoffs**
**Cost-benefit analysis**

$$P\left(\frac{\text{Benefit}}{\text{Cost}} \geq 1\right) = 1 - P(\text{Benefit} - \text{Cost} \leq 0)$$




**Data needs**

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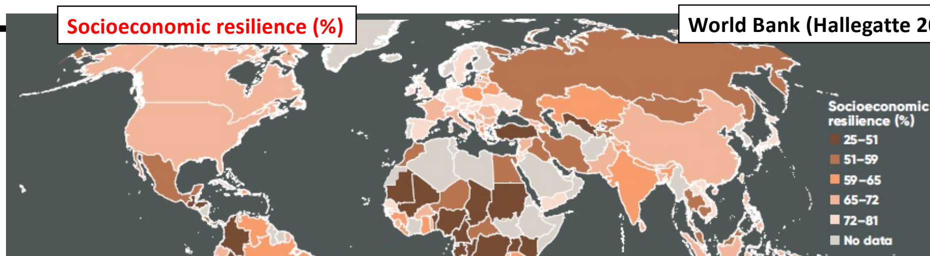
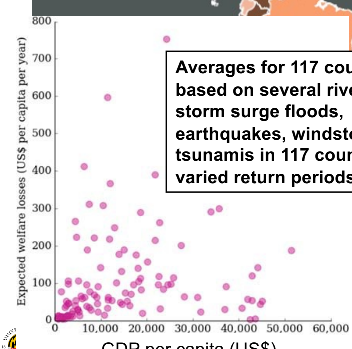
# Socioeconomic Resilience

Socioeconomic resilience (%)

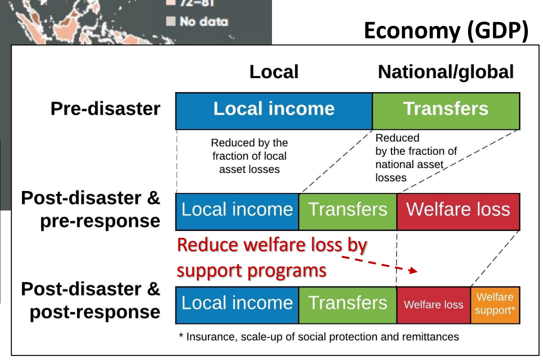
World Bank (Hallegatte 2016)




**Averages for 117 countries based on several riverine and storm surge floods, earthquakes, windstorms, and tsunamis in 117 countries varied return periods**

**Socioeconomic resilience** measures the ability of an economy (& society) to minimize the impact of asset losses on wellbeing (measured by welfare loss)




**Socioeconomic Resilience = (Asset Loss)/(Welfare Loss)**

# Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure

**2019 The Hoover Institution/Stanford University Policy document**

## Strategies

1. Make better decisions in the face of uncertainty
2. View infrastructure systemically
3. Take an iterative, multi-hazard approach
4. Improve and inform cost-benefit analysis
5. Mainstream nature-based infrastructure
6. Jump-start resilience with immediate actions
7. Plan now to build back better

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434 Galvez Mall
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202-760-3200

HOOVER INSTITUTION

## Principles

Be proactive, fair, inclusive and comprehensive

**Sources**


- Hill, A. C., Mason, D. J., Potter, J. R., Hellmuth, M., Ayyub, B. M., Baker, J. W., "Ready for Tomorrow: Seven Strategies for Climate Resilient Infrastructure," A Hoover Institution Essay, Stanford University, The Johnson Center, Washington D.C. https://www.hoover.org/research/ready-tomorrow-seven-strategies-climate-resilient-infrastructure
- Ayyub, B. M., and Hill, A., 2019, "Climate-Resilient Infrastructure: Engineering and Policy Perspectives," The Bridge, National Academy of Engineering (NAE), June 2019.


2019 briefing at the U.S. Senate
The New Green Deal (Senator Sanders)

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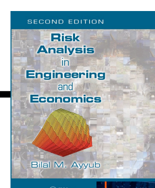
# Concluding Remarks

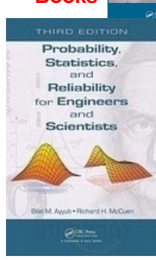
CTSM Center for Technology and Systems Management
Technology for Intelligent Decisions

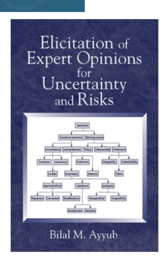
- **Climate-resilient infrastructure**: consistency across sectors and hazards
- **Measurement science**: resilience including recovery
- **Technologies** needed for **different phases** and **integration**
- **Systems and networks**
- **Economics** of resilience enhancing strategies
- **Socioeconomics** of resilience

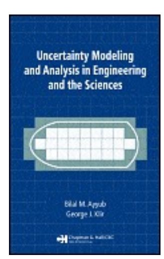
**Resources available**

**Books**

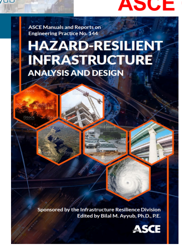


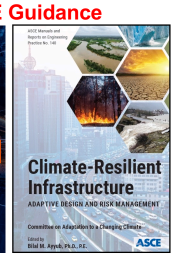



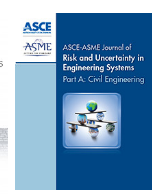




**ASCE Guidance**




**Journals**


**Call for Papers**

ASCE American Society of Civil Engineers

ASME SETTING THE STANDARD

ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems: Part A. Civil Engineering and Part B. Mechanical Engineering
More information https://en.wikipedia.org/wiki/ASCE-ASME_Journal_of_Risk_and_Uncertainty_in_Engineering_Systems
Contact: Professor Bilal M. Ayyub, Editor in Chief, ba@umd.edu

**Thank you**

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# Hazards Causing Disruptions

**The United Nations Office for Disaster Risk Reduction** **(Year 2011 as an example)**

- 302 natural disasters worldwide including the earthquake and tsunami that struck Japan
- US$364 billion in direct damages
- 30,083 fatalities
- Storms and floods accounted for 70%
- Earthquakes producing the greatest number of fatalities

Average annual losses in the US amount to about $55 billion (2011)

**Climate change is expected to increase storm intensity**

### Super Storm Sandy

- October 2012
- 305,000 homes destroyed in New York
- 2.2 million power outages
- 265,300 businesses impacted
- 121 people killed

### Hurricanes Katrina & Rita

- August 2005
- 214,700 homes destroyed in Louisiana
- 800,000 power outages
- 18,700 businesses impacted
- 1,800 people killed

**Severity: interactions between storms, and property and people**

**Community Resilience**



# Coastal Exposure (US East Coast)

**Urban Land Institute 2013**

| Coastal States | Coastal Exposure (2012 US Billions) | Total Exposure (2012 US Billions) | Coastal as a Percentage of Total |
|---|---|---|---|
| Florida | $2,800.8 | $3,562.7 | 79% |
| New York | 2,679.5 | 4,385.7 | 61 |
| Texas | 1,143.5 | 4,406.7 | 26 |
| Massachusetts | 807.2 | 1,505.1 | 54 |
| New Jersey | 706.5 | 2,081.2 | 34 |
| Connecticut | 542.5 | 843.8 | 64 |
| Louisiana | 275.1 | 790.4 | 35 |
| South Carolina | 229.6 | 814.7 | 28 |
| Virginia | 176.7 | 1,685.9 | 10 |
| North Carolina | 159.6 | 1,756.2 | 9 |
| Maine | 157.7 | 273.6 | 58 |
| Alabama | 118.7 | 903.9 | 13 |
| Georgia | 101.8 | 1,861.7 | 5 |
| Delaware | 76.9 | 200.5 | 38 |
| New Hampshire | 61.0 | 259.9 | 23 |
| Mississippi | 59.0 | 464.5 | 13 |
| Rhode Island | 55.6 | 199.5 | 28 |
| Maryland | 17.1 | 1,262.2 | 1 |
| Total, coastal states | $10,168.8 | $27,258.3 | 37% |
| U.S. total | $10,168.8 | $62,091.1 | 16% |

**Value of insurable properties along the U.S. Gulf and East coasts:**

**More than $10 trillion in 2012**

**(an increase of almost 15 percent from 2007)**